

Bigraphical Nets

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Interaction nets are a graphical model of computation, which has been used to define efficient evaluators for functional calculi, and specifically λ -calculi with patterns. However, the flat structure of interaction nets forces pattern matching and functional behaviour to be encoded at the same level, losing some potential parallelism. In this paper, we introduce bigraphical nets, or binets for short, as a generalisation of interaction nets using ideas from bigraphs and port graphs, and we present a formal notation and operational semantics for binets. We illustrate their expressive power by examples of applications.

Keywords: Interaction Net, Port Graph, Bigraph, Rewriting Calculus.

1 Introduction

Interaction nets [15] are graphical rewrite systems used for the specification of logical proof systems (e.g., [1, 16]), for the implementation of efficient evaluators for the λ -calculus (e.g., [12, 4, 18]), and for visual programming (e.g., [13, 20, 19]).

The visual nature of interaction nets makes them well suited as a specification tool, and, since *all* the computation steps are explicit and expressed in the same formalism (there is no external machinery), interaction nets are also well suited for the study of the dynamics of programming languages and rewriting systems [9, 7, 22]. However, interaction nets have some drawbacks. When the nets are large or growing during reduction, being able to *structure* the graph is crucial to understand the system modelled, but interaction nets lack mechanisms to structure the system. Moreover, to formally prove properties of the system modelled or implement reduction, a *formal, algebraic notation*, with a precise operational semantics, should also be available. In this paper, we address these two points:

- First, inspired by Milner's bigraphs [21], we define a generalisation of interaction nets, which we call bigraphical nets, or simply *binets*, where not only the connectivity but also the hierarchical structure of the system is taken into account. Binets borrow from bigraphs a notion of locality that is missing in interaction nets.
- Then, we present a formal algebraic notation for binets, with an operational semantics which can serve as a basis for their implementation.

Related Work. Binets can be seen as hierarchical graph rewriting systems that permit links between nested nets and external subgraphs (like bigraphs, and unlike hierarchical graphs [6]). Rewriting can take place across boundaries. Both of these features will be of use in our encoding of the ρ -calculus.

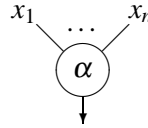
Binets inherit from interaction nets the notion of principal port. But, in contrast with interaction nets, binets do not force all interactions to be binary, and in contrast with bigraphs, they place restrictions on reactions to simplify the implementation of rule application.

Interaction nets have been used as an implementation language for functional calculi, and as a tool to understand their dynamics [12, 4, 17, 18, 8, 7, 11]. Interaction net encodings of the ρ -calculus [5], an extension of the λ -calculus where we can abstract on patterns, not just on variables, shed light on the implicit parallelism present in the ρ -calculus, and at the same time, motivate a generalisation of interaction nets, as shown in [10]. In this paper, we develop and formalise this idea. Our main contribution is a formal syntax and operational semantics for binets, via a textual calculus.

The class of portgraphs defined by Andrei and Kirchner [3] can also be seen as a generalisation of interaction nets, but although binets are graphs with ports, due to their hierarchical nature they cannot be defined as portgraphs. It would be interesting to consider a generalisation of portgraphs with a notion of locality; the inclusion of this feature in PORGY [2] could serve as a starting point for the development of a specification environment based on binets.

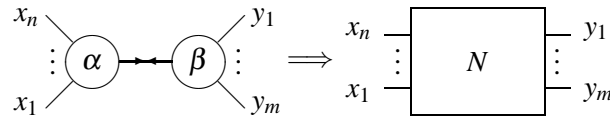
2 Background

Interaction Nets. A system of interaction nets is specified by a set Σ of symbols with fixed arities, and a set \mathcal{R} of interaction rules. An occurrence of a symbol $\alpha \in \Sigma$ is called an *agent*. If the arity of α is n , then the agent has $n + 1$ ports: a *principal port* depicted by an arrow, and n *auxiliary ports*. Such an agent will be drawn in the following way:



A net N is a graph (not necessarily connected) with agents at the vertices and each edge connecting at most 2 ports. The ports that are not connected to another agent are *free*. There are two special instances of a net: an empty net, and a net consisting only of edges (no agents). The *interface* of a net is the set of free ports of agents and free extremes of wires. We refer to [15] for more details.

An interaction rule $((\alpha, \beta) \Rightarrow N) \in \mathcal{R}$ replaces a pair of agents $(\alpha, \beta) \in \Sigma \times \Sigma$ connected together on their principal ports (an *active pair* or *redex* and written $\alpha \bowtie \beta$) by a net N with the same interface. Rules must satisfy two conditions: all free ports are preserved during reduction (there are no global operations: only the part of the net involved in the rewrite is modified), and there is at most one rule for each pair of agents (such a rule will thus be sometimes denoted by $\alpha \bowtie \beta$). The following diagram shows the format of interaction rules (N can be any net built from Σ).



We use the notation \Rightarrow for the one-step reduction relation, or $\xRightarrow{\alpha \bowtie \beta}$ if we want to be explicit about the rule used, and \Rightarrow^* for its transitive and reflexive closure. If a net does not contain any active pairs then we say that it is in normal form. The key property of interaction nets is that reduction is strongly confluent. We refer the reader to [15] for more details and examples.

Bigraphs. In [21, 14] a notion of graph transformation system is defined, using nested (or hierarchical) graphs called *bigraphs*. Bigraphs represent two kinds of structure: locality (nodes may occur inside

other nodes) and connectivity (nodes have ports that may be connected by links). We recall the basic terminology of bigraphs and refer the reader to [21] for details and examples.

A bigraph is a pair of a *place graph* and a *link graph* over the same set of nodes. It has interfaces, which define the way in which it can be composed with other bigraphs. The place graph, or placing, is a set of trees with interfaces, and the link graph, or linking, is a hypergraph with interfaces. A placing has inner and outer interfaces. The inner interface corresponds to the *sites* where other graphs can be placed, and the outer interface corresponds to the *roots* of the trees. The linking also has inner and outer interfaces, which are names of ports, that is, the points where edges can be attached.

Nodes are labelled by *controls* with fixed arities; the arity of a control corresponds to the number of ports of the node. A control is *atomic* if it cannot contain a nested graph, otherwise it is non-atomic.

The reduction relation is defined by a set of reaction rules, which are pairs of bigraphs (called *redex* and *reactum*). The redex has a *width*, corresponding to the number of sites it occupies in the outer bigraph [14]. A non-atomic control K can be specified as *active*, in which case reactions can occur inside, or *passive*, in which case reactions in the internal bigraph can only occur after the control K has been destroyed.

Interaction nets can be seen as a particular kind of bigraphs without nesting: all controls (called agents in interaction nets) are atomic, and have a distinguished port (the principal port). Interaction rules can be seen as reactions in which both redex and reactum have width 1, and redexes are restricted to just two controls connected by one link through the distinguished ports.

3 Binets

3.1 Informal presentation

Bigraphs [14] introduce a notion of locality (using nesting to indicate that a graph is local to a certain node) which is missing in interaction nets. In this section, we define binets as a generalisation of interaction nets to incorporate this feature. We start with an informal definition of binets, contrasting them with interaction nets, before presenting a formal syntax and semantics for them.

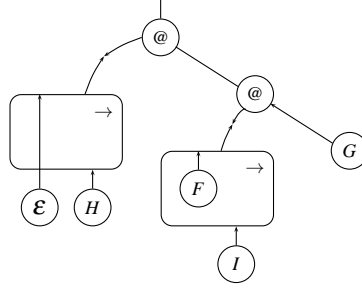
A binet is a labelled graph consisting of a set of nodes (also called *agents*) and a set of edges, which are attached to nodes at connection points called *ports*. Each edge connects at most two ports. The label of a node (i.e., the agent's name) determines its arity, that is, the number of ports it has. Each agent has a distinguished port, called the *principal* port, and a (possibly empty) set of *auxiliary* ports. An agent can be located inside another agent, and edges can connect ports of agents situated at different nesting levels (i.e., edges can cross node boundaries).

Interaction rules, also called reaction rules, define interactions between two agents connected by their principal ports, or interactions of an agent with its local subnets, preserving the interfaces.

Figure 1 shows a binet representing a ρ -term. Ovals and circles represent agents, their names are written inside; principal ports are marked with an arrow, the free port at the top is marked by a dangling edge. The ε -agent is drawn outside the \rightarrow -agent to exploit a non-strict semantics as early in the reduction process as possible.

In contrast with interaction nets, the left-hand side of a reaction rule can specify the location in which the reacting agents are, or the locations contained in these controls, and reactions can take place across boundaries. However, reduction is still local in the sense that it only affects the nodes that match the left hand side (no global conditions or updates are specified). The latter point is relevant for implementation.

Agents in binets correspond to the notion of control in bigraphs, and binet reaction rules are a particular class of bigraph reaction rules. Each binet has an associated place graph and link graph, similarly to

Figure 1: Binet for the ρ -term $(x \rightarrow H)((F \rightarrow I)G)$.

bigraphs. All the examples of bigraphs for the π -calculus and ambient calculus given in [14] (part I) can be recast as binets by adding principal ports and copy/erase agents (controls) to preserve the interface of the reactions.

Comparing with the properties of interaction nets, we remark that confluence does not hold in general for binets, because of the possibility of interactions across boundaries. To study the formal properties of binet reduction, below we give a calculus for binets.

3.2 A calculus for binets

As Milner [21] stated: “Diagrams are valuable for rapid appreciation of a system’s structure. On the other hand, algebra is essential to express [...] the ways in which a system may be resolved into components.” In this section we give a formal, algebraic presentation for binets. First we give the syntax of the language, and then we present an operational semantics for programs written in this language.

Syntax. A textual syntax for binets has to capture, dually, the connections between agents (including where those connections are principal ports), differentiating between internal or external with respect to the originating agent and also the locality of agents within a system, i.e., their physical position within other agents. It is the intention of this syntax to unambiguously state these three properties without over-complication.

We define below agents and binets over a *signature* \mathcal{A}, L , where \mathcal{A} is a set of *agent names*, each with an associated arity (n, m) corresponding to the number of ports in its internal and external interface, respectively, and L is a set of port labels. We assume $L \cap \mathcal{A} = \emptyset$.

Definition 3.1 (Agent) An agent over the signature \mathcal{A}, L is written $A^l \langle E | I | N \rangle$, where $A \in \mathcal{A}$ is the agent name, which determines its arity (n, m) , $l \in L$ is the label given to the principal port of A , and the lists I, E of lengths n, m respectively, whose elements are port labels in L , denote the internal and external agent interfaces; the order denotes the geographic position of the ports (in similar fashion to interaction nets reading in a clockwise direction from the principal port for external ports and, without loss of precision, in an arbitrary clockwise direction for interior ports). N is a (possibly empty) list corresponding to the set of agents located within the agent.

The definition above is inductive (due to the inclusion of the set N within A) but not recursive; agents are not permitted to be located within themselves.

Definition 3.2 (Binet) A binet over the signature \mathcal{A}, L is defined as a set of agents and wires over \mathcal{A}, L . Agents have already been defined. A wire is an edge joining two ports, written $a-b$ where a, b are the

labels of the ports. Each port label in L occurs at most twice in a binet; the net interface of the binet is defined as the subset of labels occurring only once.

The binet containing no agents and wires is a special case. For brevity, agents of the form $A^i\langle X | \emptyset | \emptyset \rangle$ will be denoted $A^i\langle X \rangle$ and the particular case when $X = \emptyset$ will be written $A^i\langle \rangle$.

A binet, similar to a bigraph, can be decomposed into a place graph and a link graph. The link graph is explicit in the definition of binet (a binet is a set of agents and wires); the place graph can be reconstructed from the nesting of agents.

Reduction in binets occurs on *active pairs*, which are pairs of agents connected via their principal ports, similarly to interaction nets although significantly rules in binets must be aware of locality context. More precisely, a rule may affect the agents in the place graph of the active pair. We illustrate it with an example: the interaction rule presented in [10] between the matching agent, M and any other agent α is one such occurrence and would be written:

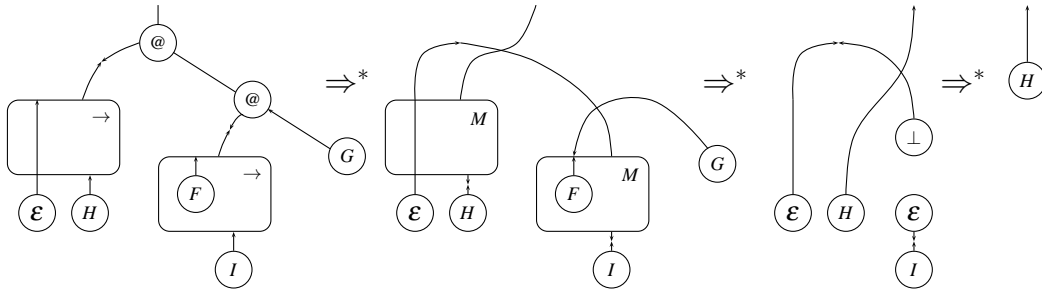
$$M^a\langle b | \emptyset | X \rangle, \alpha^a\langle Y \rangle \Rightarrow \alpha_M^b\langle Y | \emptyset | X \rangle$$

The metavariables X and Y denote a subnet and series of labels respectively that remain unchanged under graph reduction. Here, the interaction between the agents M and α causes the subgraph located within the agent M (denoted by X) to move to the new agent named α_M with principal port b .

Contrary to interaction nets, binets permit reductions to occur on certain graph configurations despite the nonexistence of an active pair, called *inactive* rewriting in the sequel. See for example the configuration in [10] of an empty matching agent, M , where the net is rewritten to a wire without interaction through active pairs. This is written as follows (the arrow explicitly shows the type of rule being applied):

$$M^a\langle b \rangle \Rightarrow_{\text{inactive}} a-b$$

The reduction calculus is defined below, but first we give an example: a reduction sequence for the binet shown in the previous subsection, representing the ρ -term $(x \rightarrow H)((F \rightarrow I)G)$. The textual representation of each binet is shown in the table below.



First Binet	Second Binet	Third Binet	Fully Reduced
$\rightarrow^x\langle a b \emptyset \rangle$	$M^a\langle c \rangle$	$H^c\langle \rangle$	$H^c\langle \rangle$
$\varepsilon^b\langle \rangle$	$H^a\langle \rangle$		
$H^a\langle \rangle$		$\perp^d\langle \rangle$	
$@^x\langle c, d \rangle$	$\varepsilon^d\langle \rangle$	$\varepsilon^d\langle \rangle$	
$@^y\langle d, e \rangle$	$M^f\langle d \emptyset F^e \rangle$		
$\rightarrow^y\langle f g F^g \rangle$	$I^f\langle \rangle$	$I^f\langle \rangle$	
$I^f\langle \rangle$	$G^e\langle \rangle$	$\varepsilon^f\langle \rangle$	
$G^e\langle \rangle$			

The second binet contains three active pairs but parallel firing of the rule for agents M^f and I^f with the rule for F^e and G^e would clearly be incorrect; the general rule for M with α involves a rewriting that affects all of the nested nets within M , hence a reduction strategy is required. Informally, there is a choice to delay either active pair until the other has had the opportunity to reduce (although in this instance either derivation will eventually lead to the intended destruction of this disjoint net). A strategy is also required in the same configuration to either fire the rule for M^a and H^a or, as in the example, to perform an inactive rewrite on M^a and reduce it to the wire $a - c$ (see the second textual rule above).

Reduction Rules. Rewrite rules follow the simplicity of interaction nets when the reductum has no rewrite implications for any agent except for the agent (in the case of inactive rewriting) or agents (active pair rewriting) directly involved. However, due to the more expressive graph rewriting allowed by binets, rewrite rules require additional machinery to resolve rewriting of nested agents within the place graph of the net. Unlike interaction net rules they incorporate metavariables and an additional strategy language.

A priori knowledge of how a rule may affect the surrounding subnet is essential when the rule is defined. For example, the ε rule within the ρ -calculus scheme is the garbage collection agent responsible for deleting nets. This agent propagates through subnets, terminating when it forms an active pair with another ε -agent, hence when defining the interaction of ε and M , the subnets within M should also be reduced, as follows:

$$\varepsilon^a\langle\rangle, M^a\langle b|\emptyset|X\rangle \Longrightarrow \varepsilon^b\langle\rangle, X, \text{foreach } x \text{ in } I(X): \varepsilon^x\langle\rangle \text{ and } \varepsilon^{\bar{x}}\langle\rangle$$

where $I(X)$ is the collection of labelled ports that constitute the interface of the nested net X and \bar{x} is a fresh label for the port outside of M that was connected to the interface at x .

The ability of binets to rewrite over agent boundaries means the efficiency (measured in the number of interactions: typical of interaction nets although cruder for binets) can be improved by rephrasing the rule to propagate ε only over the wires that are free in this subnet (i.e., those wires that extend beyond the locality of the M -agent). Each of these wires can be identified by a label appearing only once in the subnet X and so the above rule can be reinterpreted as follows, where X is removed in one step:

$$\varepsilon^a\langle\rangle, M^a\langle b|\emptyset|X\rangle \Longrightarrow \varepsilon^b\langle\rangle, \text{foreach } x \text{ in } L_X \text{ where } x \text{ is unique: } \varepsilon^x\langle\rangle$$

where L_X is the multiset of labelled ports in X .

The strategy language is left informal at this stage with full details to be provided in later technical reports.

Reduction Calculus. The reduction calculus comprises four main parts: firstly populating a set of the active pairs within a binet and also those (sub)nets that are configured in a way that permits inactive rewriting. This collection of active pairs and nets is then prioritised according to a given reduction strategy and, crucially, a collection of agents and nets that can safely be rewritten in parallel is identified. Then, both active and inactive rewriting is performed and, lastly, a tidying stage is performed to eliminate every explicitly written wire in the net.

Collect Let \mathcal{C}_A be the set of labels of principal ports involved in active pairs (these are easily computed: scan the graph and identify each label l that appears twice as a principal port) and \mathcal{C}_I be the set of binets that are isomorphic to the left hand side of inactive rewriting rules (computed using standard subgraph matching algorithms that can be optimised due to occurrence of principal ports).

- Prioritise** According to the reduction strategy implemented (weighted, stochastic, typed and so on) group all *safe* nets, \mathcal{C}_s . A collection of safe nets is one where rewriting (either active or inactive) can occur in parallel without conflict. The safety, or otherwise, of potential net rewriting is inferred by the rules: any rule of the form $\alpha^m \langle - | - | X \rangle, \dots \Longrightarrow \beta^n \langle - | - | X' \rangle$ where $X \neq X'$ cannot safely be rewritten at the same time (or in the same *pass*) as any rule that rewrites within X .
- Rewrite** For each active pair and agent within \mathcal{C}_s , apply rule. For simple rules where rewriting does not occur within agent borders and there are no internal edges:

$$\begin{aligned} \alpha^x \langle u_1, \dots, u_m \rangle, \beta^x \langle v_1, \dots, v_m \rangle &\Longrightarrow \Gamma_1^{w_1} \langle w_2, \dots, w_p \rangle, \dots, \\ &\quad \Gamma_q^{w_r} \langle w_{r+1}, \dots, w_s \rangle, \\ &\quad u_1 - w_i, \dots, u_m - w_{i'}, \\ &\quad v_1 - w_{i''}, \dots, v_n - w_{i'''} \end{aligned}$$

where Γ^w are the (possibly empty) agents that are produced on rewriting and \mathbf{w} are the intermediary labels given to the wires of the produced net. Note that the size of \mathbf{w} is potentially larger than the number of ports to the left hand side of the rule. The cases for rules whose agents have internal ports and rewriting occurs across borders incorporates a richer programmatic syntax and the resulting operational calculus is more complex.

Tidy If w is a label within Γ and there exists $u - w$ then substitute w by u within Γ ($\Gamma[w/u]$).

4 Conclusion

We have presented a new visual language generalising interaction nets to incorporate features from bi-graphs. Domains of application include concurrent and reactive systems. Not only can binets model these systems both graphically and textually, but they are also directly implementable. We are currently working on the implementation of an abstract machine for binets, inspired by the interaction net machines defined in [22].

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